CHAPTER I

PLANT AND AIR TEMPERATURE PATTERNS IN ALFALFA, CORN, GRASS, SORGHUM AND SOYBEANS AS MEASURED WITH THERMOCOUPLES AND INFRARED THERMOMETERS

B. L. Blad, B. R. Gardner, S. Steinmetz and N. J. Rosenberg

ABSTRACT

Results of studies comparing temperature measurements made with an infrared thermometer and with attached leaf thermocouples have raised several questions, such as: 1) to what extent do crop type, leaf area, percent cover and stage of growth affect agreement between the two methods of measurements?; 2) where should leaf thermocouples be placed in a plant canopy in order to provide a representative measure of crop temperature?; 3) how does moisture stress influence the measurement of crop temperature?; 4) how does planting pattern affect crop temperature measurement? A study designed to answer these questions and to provide further understanding of factors that affect the agreement of leaf thermocouples and infrared thermometers is reported here.

Plant and air temperatures were measured in Nebraska on plots of alfalfa, corn, grass, sorghum and soybean with an infrared thermometer (IRT) and with evanohm-constantan thermocouples at three levels within the canopy. Data were collected during three 24-hour periods in 1976 and again throughout the 1978 growing season.

Prior to the achievement of 75% crop cover, infrared thermometer temperature (T_{IR}) during daytime was consistently warmer than the thermocouple temperature (T_{TC}) of sunlit leaves. The

difference in results between the two methods was dependent on canopy cover. With greater than about 80% cover, T_{IR} was generally within ±1 C of sunlit leaves.

At night, the lower leaves of all crops were warmer than the upper leaves. T_{IR} was 1 to 3 C warmer than the upper leaves, but was generally within 1 C of the lower leaves. This suggests that, at night, T_{IR} is influenced by soil temperature and that better estimates of plant temperatures are obtained with leaf thermocouples than with infrared sensing devices, especially for vertical viewing angles.

Daily leaf and air temperature profiles in all crops were similar. Profiles tended to be lapse before crop cover was complete and inverted later in the season.

T_{IR} of fully irrigated corn agreed with T_{TC} to within 1.2 C during the daytime. The daytime agreement between T_{IR} and T_{TC} among stressed corn plants was 2.6 C. The mid-day differences in T_{TC} between two non-irrigated plants spaced 2 meters apart was as great as 5.9 C. Thus, sampling problems will make it difficult to estimate an average T_{TC} in moisture stressed crops. At mid-day alfalfa was about 1.0 to 1.5 C cooler than soybeans, 3.5 C cooler than sorghum and 8.5 C cooler than grass. This suggests that the rate of evapotranspiration in alfalfa was greater than soybeans which was greater than sorghum. Evapotranspiration rate in the grass was the lowest of any of the crops.

INTRODUCTION

Many factors, including soil temperature, percent cover and leaf area index, may influence the agreement between crop

temperature as measured with leaf thermocouples (T_{TC}) and with an infrared thermometer (T_{IR}). One would expect that the factors named should affect mainly T_{IR} because of the area "viewed", and consequently the radiation sensed, by the infrared thermometer. However, the agreement may be affected, as well, by sampling difficulties inherent in the use of attached leaf thermocouples, a very large number of which may be needed to obtain an average canopy temperature.

Lourence et al. (1965) found that the major disagreement between T_{IR} and T_{TC} in tall fescue occurred during the daylight hours. They stated that the leaf thermocouples overestimated the surface temperature of the crop due to radiation errors. At night, however, T_{IR} was generally warmer than T_{TC}.

Landsberg et al. (1974) used two sets of five thermocouples each attached to leaves spaced evenly through the canopy of an apple tree in order to estimate the average leaf temperature. They also measured the temperature of sunlit and shaded leaves with an infrared thermometer (IRT). Their results show that the average leaf temperature, measured with the randomly distributed thermocouples, was within the range of temperature of sunlit and shaded leaves measured with the IRT.

Blad and Rosenberg (1976) found that the temperature of alfalfa measured with leaf thermocouples and with an IRT failed to agree consistently to within 1 to 2 C, although occasionally, agreement was better than 0.5 C. Agreement improved as the crop cover increased and it was generally best during mid and late afternoon and worst in the early morning.

There is, as yet, insufficient information concerning the

influence on T_{IR} of the soil temperature, percent cover or type of canopy. Blad et al. (1975), for example, observed that the type of canopy and the percent cover in millet and sorghum fields affected the agreement between T_{IR} and T_{TC}. Agreement was better for millet than for sorghum, especially late in the growing season when the crop was well established. They also found that the daytime agreement was much better (1 C) than that at night (1 to 3 C).

MATERIALS AND METHODS

Studies were conducted in 1976 at the University of Nebraska Agricultural Meteorology Laboratory near Mead, Nebraska (41° 09' N; 96° 30' W; 354 m above m.s.l.) and at the Sandhills Agricultural Laboratory (SAL) near Tryon, Nebraska (41° 37' N; 100° 50' W; 975 m above m.s.l.) in 1978.

1976 Study

In the Mead experiment measurements were made on plots of alfalfa (*Medicago sativa* L.); sorghum (*Sorghum bicolor* L. Moench); grass (*Festuca elatior*) and soybean (*Glycine max* L.). Each plot was ten meters long (N to S) and three meters wide (E to W).

Sorghum and soybeans were both planted on May 21, 1976 in two different planting systems, row and broadcast. Rows were 50 cm wide and the plants were spaced about 3 cm apart. Seeds of sorghum and soybean were also broadcast in a planting pattern that assured early and complete ground cover (Fig. 1). All plots were irrigated to field capacity on July 21. No additional irrigations were made until the end of the experiment.

Crop temperature, soil moisture, plant height and percent

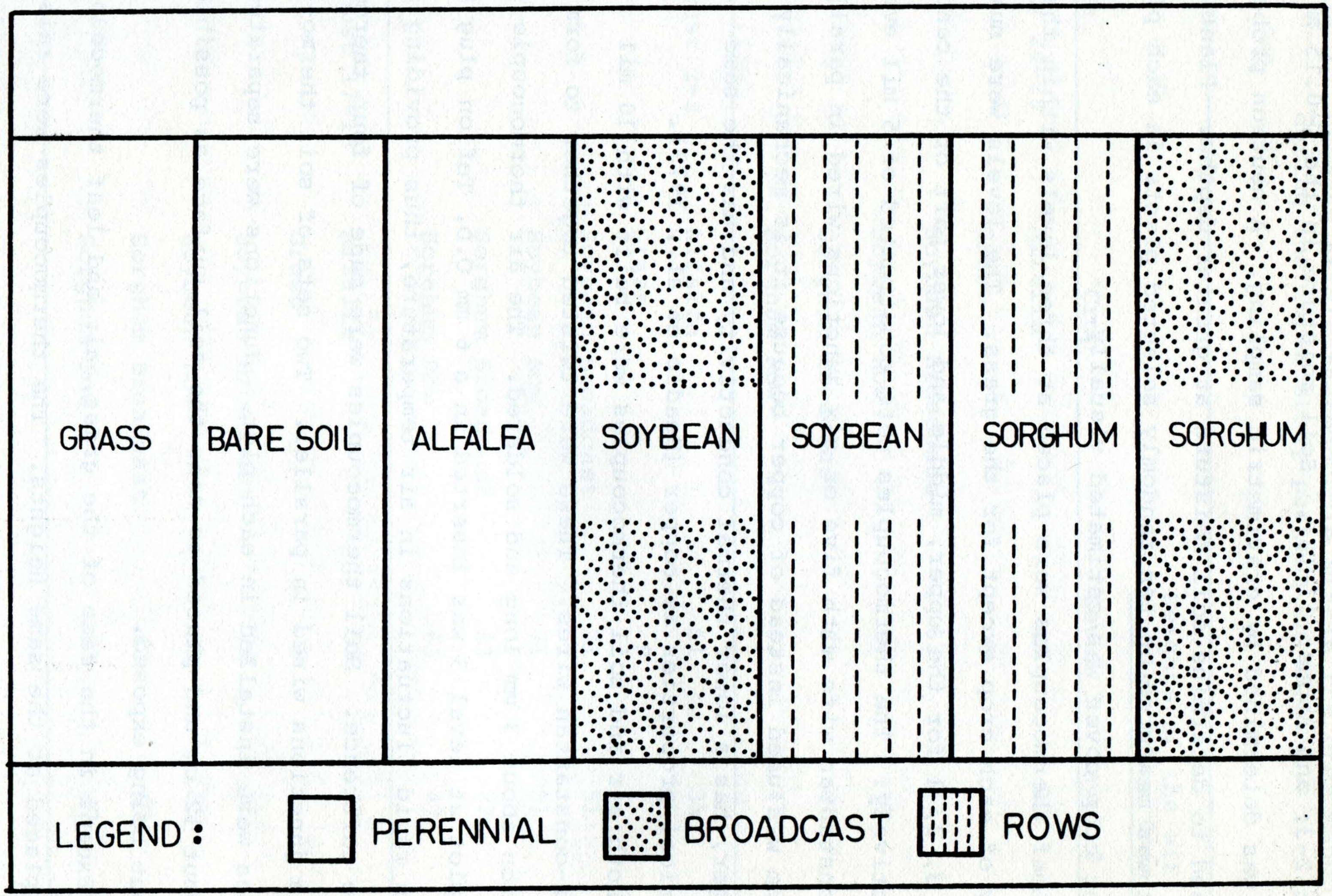

Fig. 1. Field layout of the various experimental plots and planting patterns at Mead (1976).

crop cover were measured during each of three periods (July 24-25; August 2-3; and August 17-18). Soil moisture in the 0-0.15 m layer was determined by gravimetric sampling. A neutron probe was used to determine soil moisture at greater depths. Plant height was measured on ten randomly selected plants in each plot. Percent crop cover was estimated visually.

Leaf thermocouples were placed at three levels within the canopy of each crop except for the grass. The levels were numbered 3, 2, 1 for the upper, middle and lower part of the canopy, respectively. The thermocouples were constructed of 5 mil evanohm-constantan wire with five or six junctions wired in parallel. Evanohm was used instead of copper because it is mechanically stronger, has a lower thermal conductivity and has the same electrical properties as copper (Beadle et al., 1973).

Both air and soil thermocouples were built with 10 mil copper-constantan wires. These were twisted together to form a junction about 3 mm long and soldered. The air thermocouple in each plot at level 3 was inserted in a 6 mm O.D. Teflon plug to dampen rapid fluctuations in air temperature, thus providing a stable reference. Soil thermocouples were made of four thermocouple junctions wired in parallel. Two sets of soil thermocouples were installed in each plot. Junctions were separated by about 12 cm and placed as near the soil surface as possible without being exposed.

Except in the case of the grass, air and leaf thermocouples were placed at the same heights. The thermocouples were raised as the crops grew (Table 1). The air thermocouples were radiation

Table 1. Heights of air thermocouple within the crop canopy during the three study periods in 1976.

Date	Crop	Heights of the air thermocouples in cm from ground		
		Level 3	Level 2	Level 1
July 24-25	Alfalfa	43	23	11
	Grass	6		
	Soybean Broadcast	63	43	19
	Soybean Row	59	39	19
	Sorghum Broadcast	63	47	31
	Sorghum Row	63	47	31
August 2-3	Alfalfa	51	35	19
	Grass	9		
	Soybean Broadcast	71	51	27
	Soybean Row	71	51	27
	Sorghum Broadcast	63	27	31
	Sorghum Row	63	47	31
August 17-18	Alfalfa	53	37	21
	Grass	9		
	Soybean Broadcast	79	55	35
	Soybean Row	79	55	35
	Sorghum Broadcast	63	67	31
	Sorghum Row	63	47	31

shielded with a Mylar shield 8 cm in diameter.

Difficulties were encountered in finding a practical and efficient method to attach thermocouples to the leaves. The best results were obtained in the following way: the thermocouple junctions were bent at an angle of 60-90 degrees about 3 mm from their beads. A small piece of filament tape was placed several mm from the bead and used to hold the thermocouple against the leaf. An additional strip of tape was placed 1-2 inches from the junction for mechanical support. In this way the thermocouple was, essentially, spring loaded against the leaf.

A Barnes model IT-3 IR thermometer was used during the 1976 study. The infrared thermometer (IRT) was mounted 3 m above the ground on an arm extending from a cart. The cart was pulled manually between predetermined stations in each plot. The IRT "viewed" the ground vertically. In the soybean and sorghum row plots, the IRT was placed to view one area within the rows and another area between the rows. Results showed that the temperature of these two areas were similar.

The IR thermometer was calibrated using a procedure similar to that of Conaway and van Bavel (1966). That procedure is described in detail by Blad and Rosenberg (1976). The emissivity of each crop was estimated by the method of Fuchs and Tanner (1966) except that a large plastic garbage can, covered on the inside with aluminum foil, was used instead of the "pop tent." The container had one hole in the closed end where the sensing head of the IRT was placed.

Emissivity of the crops was determined on the night of August 23, 1976 when the sky was completely clear. Readings

were made over a normal sorghum crop and again with the heads removed. Emissivity was calculated separately for each of the two planting patterns (row and broadcast) in soybean and sorghum (Table 2).

1978 Study

In the study conducted at the Sandhills Agricultural Laboratory, plant temperature measurements were made on a plot of corn (Zea mays, c.v. Pioneer 3780) which was differentially irrigated. The plot measured 27 meters (N to S) by 19 m (E to W). The plot contained 24 rows spaced at 0.76 m. The differential irrigation consisted of applying full irrigation (100% of transpiration demands) to row 1 and applying progressively less moisture to each succeeding row until, in rows 22 to 24, essentially no irrigation water was received.

Leaf temperatures were measured at three levels within the canopy on rows 2, 6, 10, 14, 18 and 22. Leaf temperatures were recorded at hourly intervals throughout the growing season. This experiment is described more fully in Chapter 2.

A Telatemp Model 44 and a Barnes PRT-5 were used to measure crop temperature. A crop emissivity of 0.97 was established on the night of June 3. The IRT was used with viewing angles ranging from 15 to 22 degrees from the horizontal.

RESULTS AND DISCUSSION

Agreement Between Leaf Thermocouples and Infrared Thermometers

One of the major problems associated with measuring canopy temperatures with IRT's is distinguishing the true plant temperatures when bare soil is also viewed by the sensor. The degree

Table 2. Emissivity of bare soil and six vegetative surfaces, determined on August 23, 1976.

Crop	Planting Pattern	Emissivity	
		Normal	Heads Removed
Alfalfa		.981	
Grass		.977	
Bare Soil		.954	
Soybean	Rows	.976	
Soybean	Broadcast	.971	
Sorghum	Rows	.971	.974
Sorghum	Broadcast	.971	.974

to which bare soil biases canopy temperature measurement depends on several factors, including viewing angle of the IRT, temperature and emissivity differences between soil and the canopy, percentage of soil seen by the IRT and solar elevation angle. Millard et al. (1978) have suggested that, especially when crop cover is sparse, a relationship between canopy temperature, plant temperature and percent bare soil is needed. This need is felt particularly when canopy temperatures measured by airborne sensors are to be correlated with actual plant temperatures. No such relationship has yet been reported in the literature.

Large differences in the soil surface temperature of irrigated and non-irrigated areas occur following irrigation. For example, on June 9, 1978, prior to irrigation, the difference in soil surface temperature, as measured with an IRT, between an irrigated and non-irrigated area was 0.5 C. Following irrigation on the next day, the soil surface temperatures were 15.9 C lower in the irrigated area.

The Mead experiment in 1976 did not begin until 75% crop cover had been reached. In 1978 at SAL, data were collected from the time of corn crop emergence. Until 40% cover was achieved, bare soil caused IRT temperatures to differ by as much as 13 C from thermocouple measurements of non-stressed sunlit leaves (Fig. 2).

Between 40 and 80% crop cover, T_{IR} temperatures tended to be lower than T_{TC} values of sunlit leaves. T_{IR} values probably reflect the influence of the cooler shaded soil and the shaded leaves of the lower canopy.

After 80% crop cover was achieved, the IRT viewed almost no

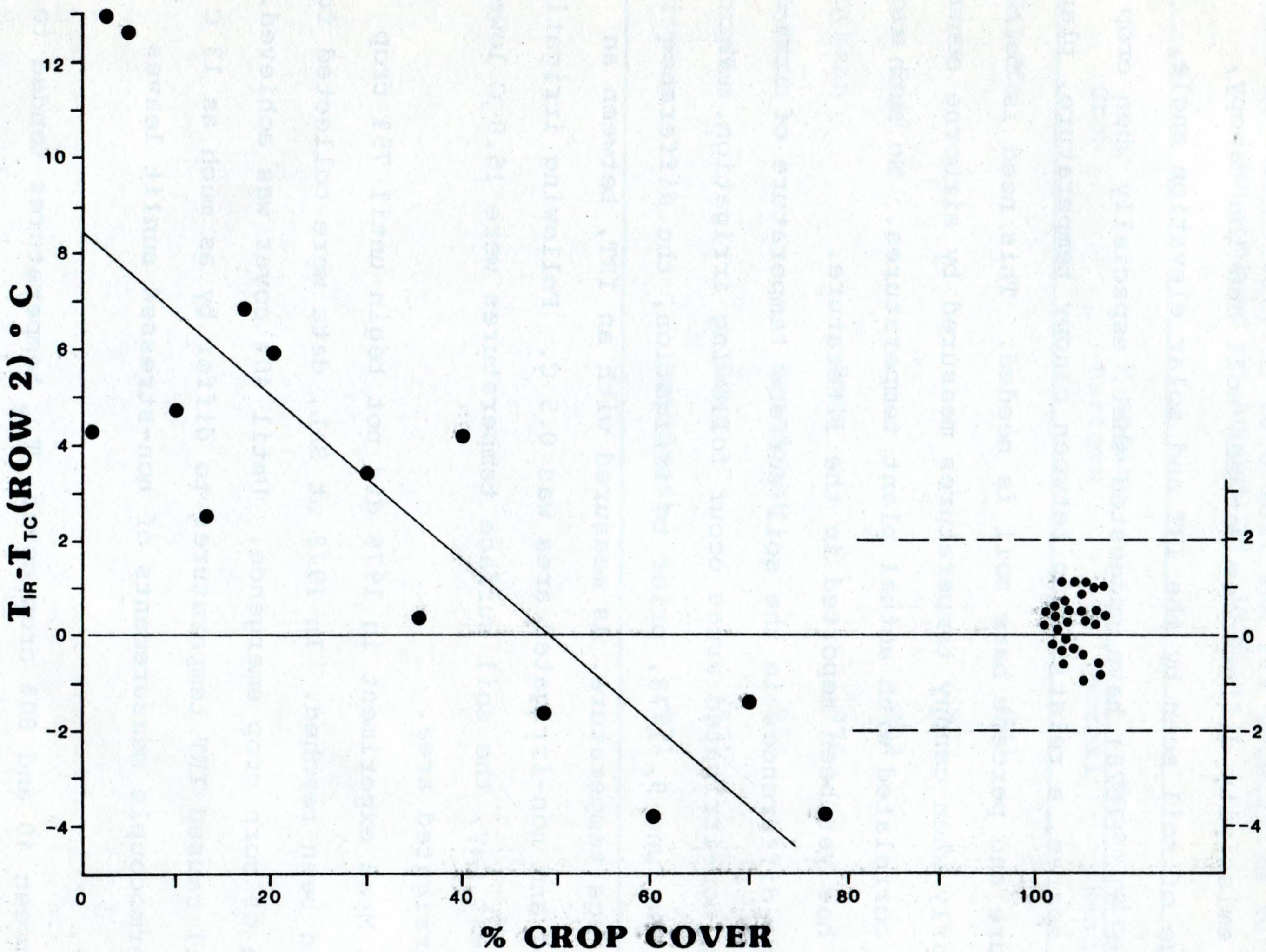

Fig. 2. Canopy temperatures of corn as measured with an IR thermometer (T_{IR}) and with leaf thermocouples (T_{TC}) as influenced by percent crop cover. Data were obtained in 1978 at the University of Nebraska Sandhills Agricultural Laboratory.

soil. Then the IRT and leaf thermocouple temperatures agreed to within 1.2 C (Fig. 3). This agreement is, however, dependent on plant moisture stress since stress increases the plant to plant temperature variability. T_{TC} values of sunlit leaves in stressed corn plants 2 m apart differed as much as 5.9 C. Thus to find representative areas for sampling with thermocouples is very difficult, especially if plants are subjected to water stress. Infrared thermometry appears, therefore, the more likely method for measuring average canopy temperature of crops under moisture stress.

A typical daily pattern for T_{IR} and T_{TC} within the canopy of row-planted soybeans is given in Fig. 4. T_{IR} agreed better with T_{TC} of the sunlit leaves than with T_{TC} values for either of the deeper levels.

A different pattern of agreement between values of T_{IR} and T_{TC} was observed in the plots of row-planted sorghum (Fig. 5). T_{IR} agreed about equally well with thermocouple temperatures at the bottom, middle and top of the canopy. Since the temperature at these three levels was nearly isothermal during each study period, it appears that placement of thermocouples in canopies with structure similar to sorghum may be less critical than in crops with canopies similar to those of soybean and alfalfa.

T_{IR} and T_{TC} did not agree well in the grass plot. A layer of dry grass near the surface of the ground, tended to "mulch" the soil. This non-transpiring material became warmer than either the soil surface or the green grass with the result that, under conditions of high radiative flux densities, the IRT temperatures were as much as 6 C greater than those measured with thermocouples.

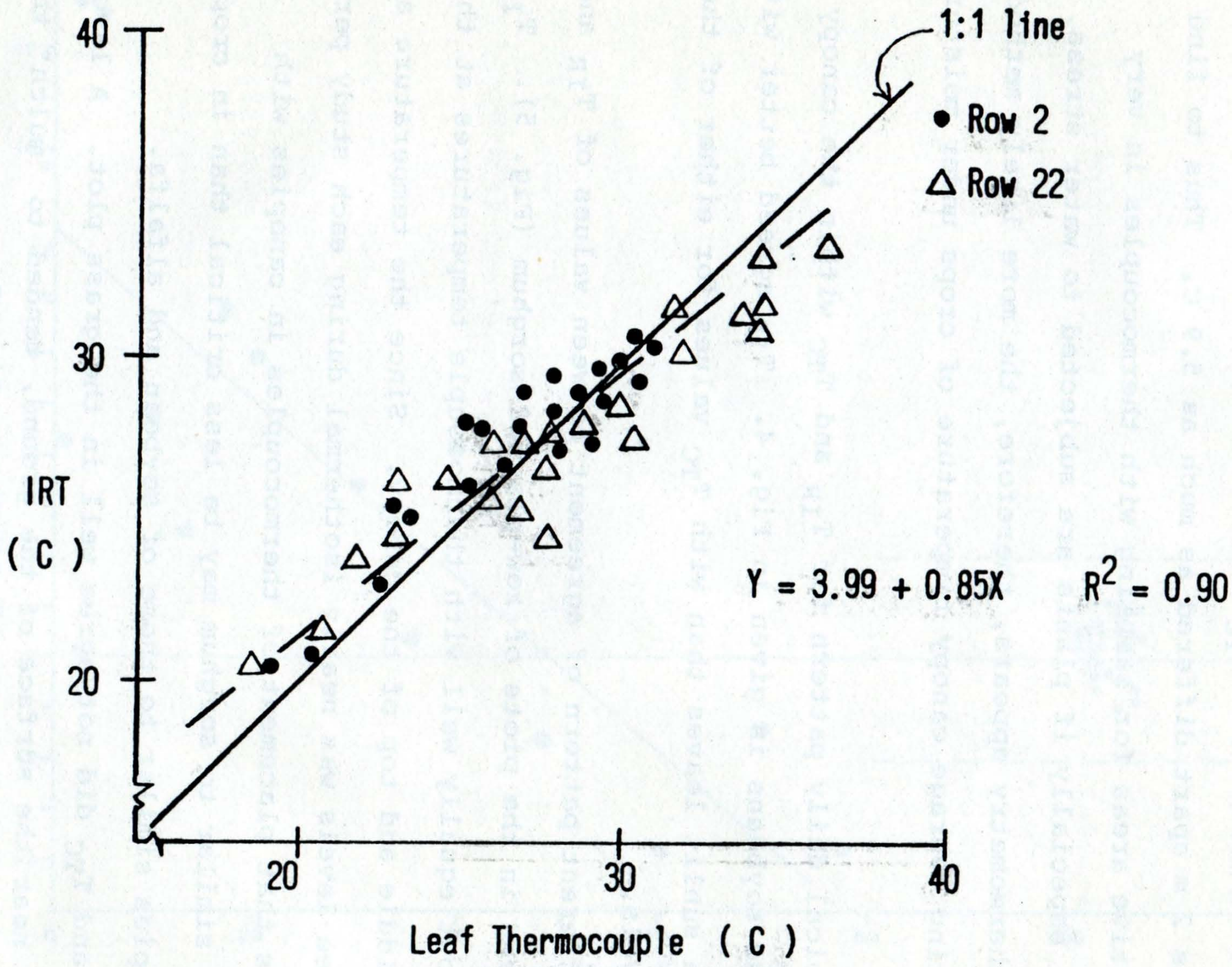

Fig. 3. Mid-day canopy and leaf temperatures of corn as measured with an IR thermometer (IRT) and leaf thermocouples, respectively. Data are from row 2 (non-stressed) and row 22 (stressed) on 26 clear days between July 19 and September 6, 1978.

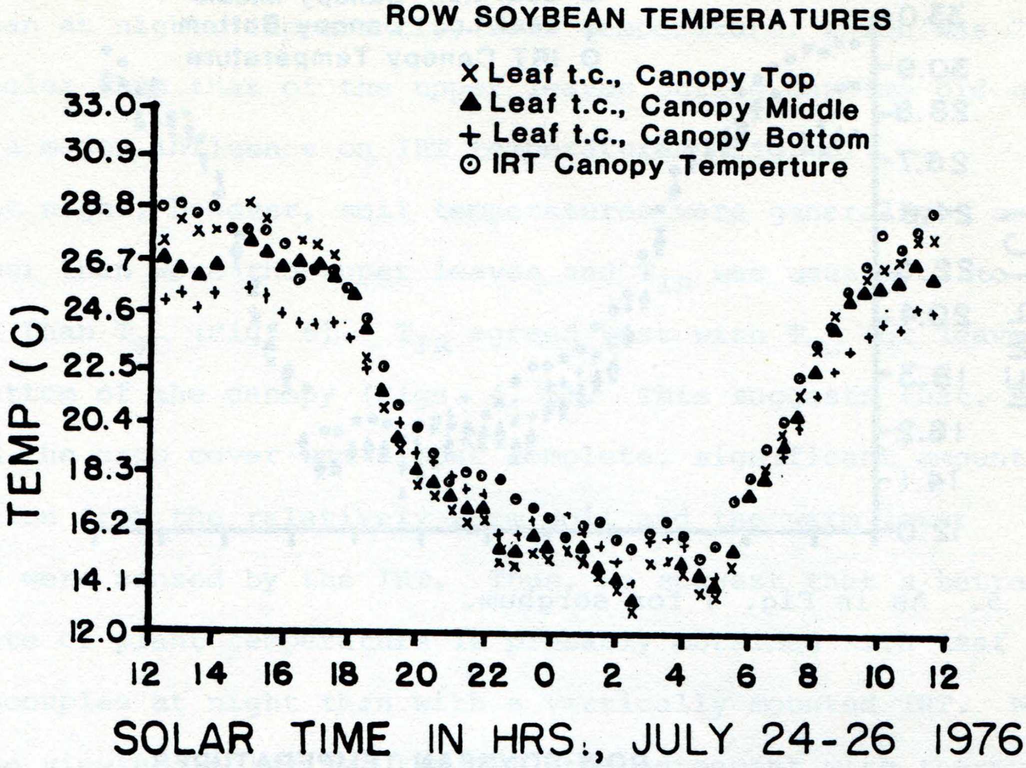

Fig. 4. Daily pattern of the canopy temperature of soybeans as measured with an IR thermometer (T_{IR}) and with leaf thermocouples (T_{TC}) placed at three levels within the soybean canopy. Data were obtained at the University of Nebraska Mead Field Laboratory in 1976.

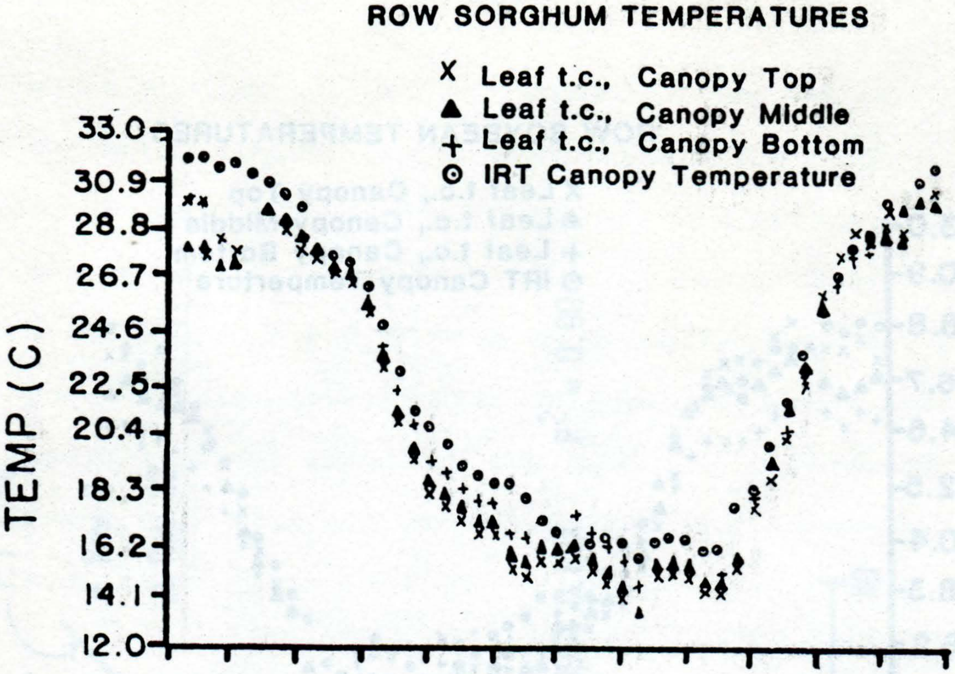

Fig. 5. As in Fig. 4 for sorghum.

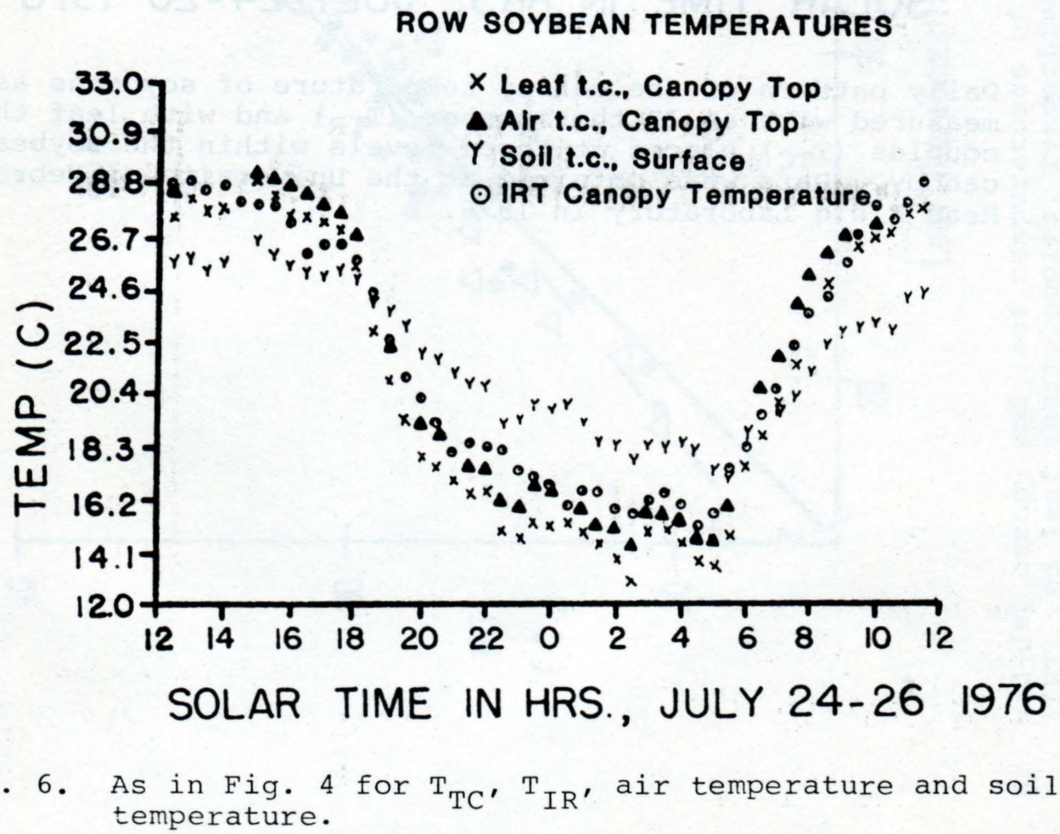

Fig. 6. As in Fig. 4 for T_{TC}, T_{IR}, air temperature and soil temperature.

Daily Patterns of Air Temperature Within Canopy

Air temperature patterns were similar for all crops after 80% cover had developed. Daytime profiles were generally inverted and nighttime profiles were nearly isothermal. This general pattern is illustrated with data for corn (Fig. 7). Prior to 80% crop cover, air temperature profiles in the corn canopy were lapse throughout the day changing to a slight inversion at night (Fig. 8).

Comparison of T_{IR}-Sensed Temperatures in Various Crops

Alfalfa was the coolest of the four crops grown in 1976 according to IRT measurements (Fig. 9). At midday soybeans were about 1 to 1.5 C warmer, sorghum was about 3.5 C warmer and grass was approximately 8.5 C warmer than alfalfa. Our results for sorghum and soybeans agree with those of Heilman et al. (1976) who found that soybeans were about 2 C cooler than sorghum. The elevated T_{IR} in grass was probably due to the influence of the layer of non-transpiring dead grass mulch which covered the soil surface. At night IRT temperatures were virtually identical in each of the four crops.

In general, the temperature of a plant is inversely related to its transpiration rate. Based on this premise, we estimate that the water use for the four crops was in the following order: alfalfa > soybeans > sorghum > grass.

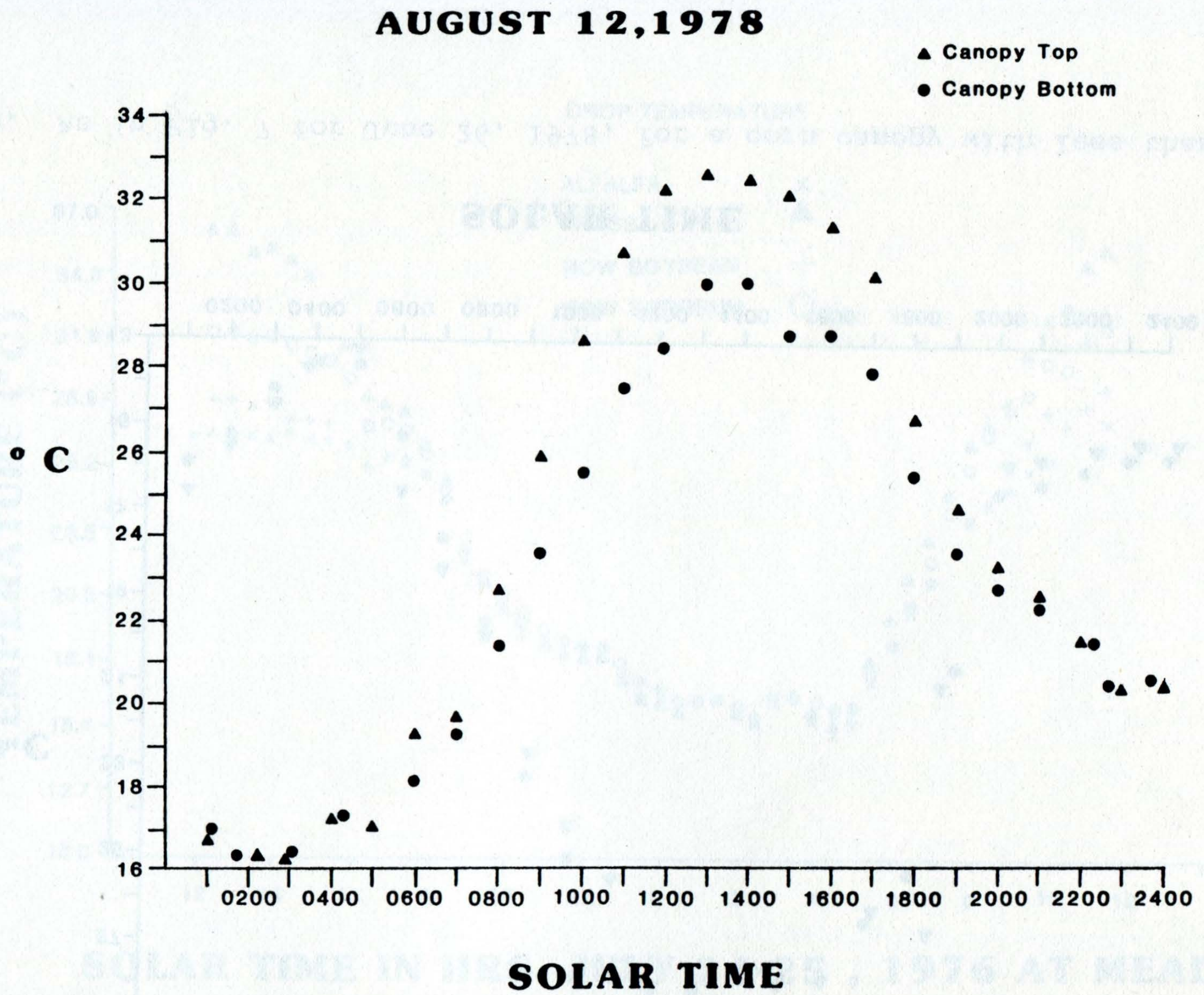

Fig. 7. Air temperature at the top and bottom of a corn canopy with complete cover on August 12, 1978. Data are from the Sandhills Agricultural Laboratory.

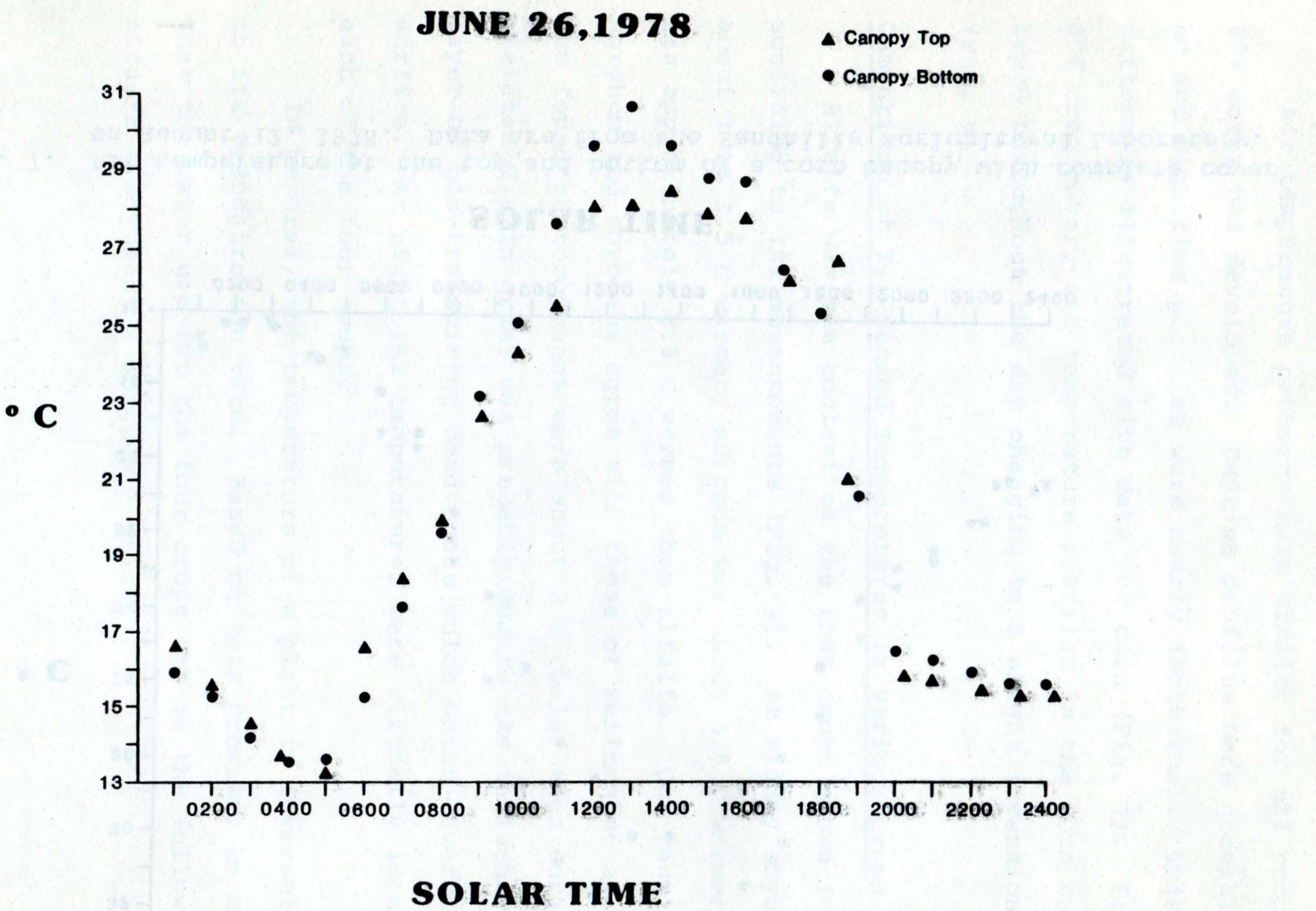

Fig. 8. As in Fig. 7 for June 26, 1978, for a corn canopy with less than 80% crop cover.

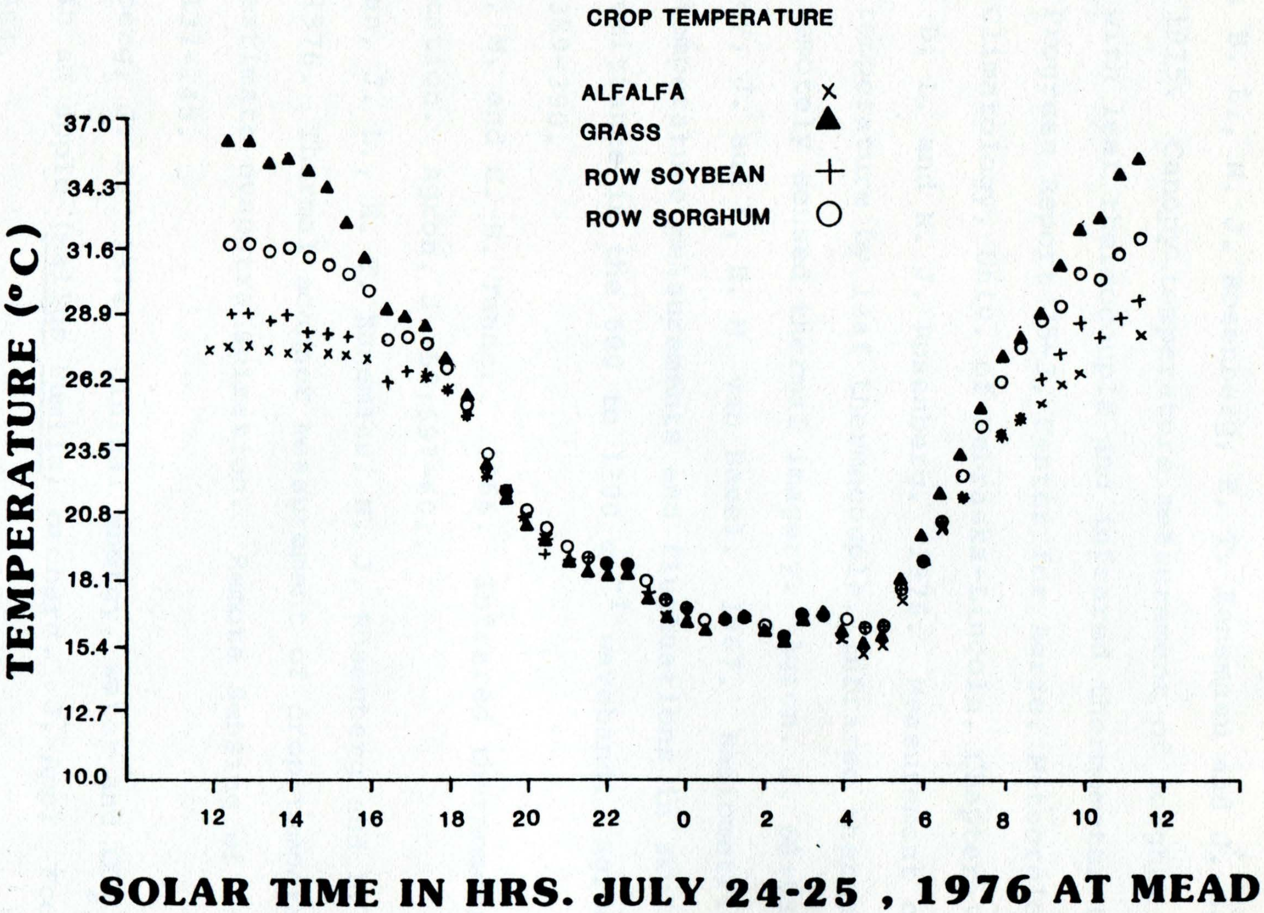

Fig. 9. Canopy temperatures of alfalfa, grass, soybean and sorghum as measured with an IR thermometer (T_{IR}). Data are from Mead Field Laboratory in 1976.

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